Developing a novel flare prediction method based on the Debrecen sunspot data catalogue

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Thesis leaflet

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Introduction

The interaction of solar activity with the Earth's upper atmosphere occurs through a complex series of events, commonly called as Space Weather. In this context, solar activity can be separated into four components: solar flares, coronal mass ejections (CMEs), high-speed solar wind, and solar energetic particles. From these events, the two most energetic are the flare and CME eruptions. Namely, high-energy flare eruptions (above the M5-class flare) can cause long-lasting radiation storms in the Earth's upper atmosphere and trigger serious radio or data communication blackouts. CMEs themselves are potentially even more hazardous than flares. They are large clouds of magnetised plasma that could impinge upon the Earth's upper atmosphere. These interactions often result in rather dramatic consequences to the functioning of a number of ground- (e.g. pipelines, power lines) and space-based infrastructures (satellites, communication, GPS) as they may be damaged. These societal assets and services are vital to the economic welfare and security of every citizen. Considerable failures due to flares and CMEs have indeed befallen in the past (e.g. Quebec, Canada suffered an electrical power blackout in 1989). The known largest and most dangerous solar eruption avoided Earth by $\sim$30 degrees only in 2012. The frequency of these most energetic eruptions of the entire Solar System follows the 11-year solar cycle, hinting towards their magnetic solar origin. At the peak of the cycle, even several dangerous flares and CMEs may occur, i.e. around monthly 2-3. Major international funding bodies, e.g. NASA, NSF or the EU Horizon 2020, have it all high in priority on their research strategy agenda to support research towards predicting reliably and accurately these solar eruptions and to protect us all from Space Weather events in the era of human space exploration.

Scientific rationale of the Thesis

The magnetic energy that fuels solar flares and CMEs is provided by the electric current-carrying component of the solar active region (AR) magnetic field, built-up gradually only to be released impulsively in eruptions. The components of the electric current density cannot be observed directly. To develop a reliable flare and/or CME prediction method, the best is if the post-events are analysed to assemble a precise global picture of the scenarios. Therefore, recent research has focused on the pre-cursive indirect observable signatures of currents and the associated stored free magnetic energy (known as signatures of non-potentiality) to identify diagnostically reliably the pre-flare/CME properties. Nowadays, the prediction methods usually attempt to find a relationship between flare and/or CME eruptions and some defined precursors. One of the most promising such observable is the magnetic polarity inversion lines (PIL) that separate regions of opposite polarities in a δ-spot of an AR.

During my PhD period, I have worked on the development of our own new prediction method by employing the SOHO/MDI - Debrecen Sunspot Data (SDD) sunspot data to find unique predictive signatures for the expected flare onset time and also for their intensity. In order to address these aims, specifically, we investigated the pre-flare dynamics and the related physical processes at the solar surface by SDD catalogue.

Our aims are achieved by the objective of developing a new type of measure of magnetic non-potentiality by employing a range of sunspot data, while most earlier flare forecasting methods are based on AR magnetograms. Sunspots are discrete entities instead of the continuous magnetic field distributions of the magnetograms. They are loci of high flux densities, so they are presumably the dominant components of the flare processes. Especially, large energetic flares take place where a distinctive PIL is formed between the strong positive and negative magnetic polarity umbrae in a δ-spot, because, this is the area where the horizontal gradient of the magnetic field is high. Therefore, in the observational and numerical studies of the dynamics of ARs one often focus on the changes in the magnetic fields near the PIL.

We also analyse the pre-flare values and the behavior of the horizontal gradient of the LOS component of the magnetic field in a δ-spots in order to find and identify indicative values of the imminent flaring behavior even up to two-three days prior to the actual flare occurrence. We track the temporal evolution of the horizontal gradient of LOS component of the magnetic field in ARs, as flare pre-cursors, with about an hourly resolution, for predicting energetic flares.

Making a novel step ahead in flare forecasting

First, we identified the horizontal gradient of LOS component of magnetic field with a proxy (G_M), which measures the magnetic non-potentiality at the photosphere. The G_M is determined between two opposite polarity umbra-pair within a δ-spot. The G_M is investigated with the aim to identify unique pre-flare patterns and improve the prediction of the occurrence of flares. We have shown that the pre-flare behaviour of this proxy quantity exhibited indeed *characteristic and unique patterns*: steep rise, high maximum and a gradual decrease prior to flaring. The prediction method based on the evolution of G_M allowed us to elaborate on some of the most important properties of an imminent flare; its intensity and the flare onset time. The prediction of intensity is found to be more reliable, for a linear relationship found between the pre-flare maximum of G_M and the peak intensity emitted in the 1-8 Å range, according to Geostationary Operational Environmental Satellite (GOES) X-ray measurements. This result may also be considered to be an *indicator of the existing relationship* between the proxies of free and released energies. Next, the onset time prediction was found to be somewhat less precise, for the most probable time of flare onset being between 2-10 hours after the G_M reaching its maximum.

Next, we generalised the G_M method and presented the concept of the weighted horizontal gradient of the magnetic field, WG_M. The introduction of the WG_M has enhanced the application capability by indicating a second flare precursor. Namely, the barycenters of the area-weighted centers of the positive and negative polarity umbrae within a δ-spot. The barycenters display a pattern of converging and diverging motions prior to the flare. We found that flares occur when the distance between the barycenters is approximately equal to the corresponding distance at the beginning of the convergence phase. This precursor has the capability for a more accurate prediction of the time of flare occurrence. The estimation of the flare onset time, is based on the relationship found between the duration of diverging motion of the opposite polarities until the flare onset and duration of the converging motion of the opposite polarities.

Next, we confirmed the linear relationship between the values of the maxima of the WG_M (WG_M^{max}) and the highest flare intensity of an AR(s). We also reported that if one can identify concurrently the two pre-flare behaviours discussed above, then flare(s) do indeed occur in the data sample. We have also shown that if one of the required pre-flare patterns is absent then a flare may not be expected.

Furthermore, we also investigated separately the single-flare case when only one energetic flare took place after WG_M^{max} and cases when multiple flares erupted after reaching WG_M^{max}. The percentage difference ($WG_M^{\%}$) was calculated between the value of WG_M^{max} and the first value of the WG_M after the flare peak time (WG_M^{flare}). We found the following empirical result: if $WG_M^{\%}$ is over 54%, no further flare of the same class or above would be expected; but, if $WG_M^{\%}$ is less than ~42%, further flare(s) of the same class is probable within about an 18-hour window.

However, it is important to recall that we can only apply the WG_M method if an AR has a δ-spot. Therefore, we have developed a method that helps us to determine which AR has a high magnetic complexity, because this fact very often gives a hint that the AR has a δ-spot. This proposed approach gives an excellent pre-selection idea for the application of the WG_M method in a future when we would like to automate this method.

Characterisation of the level of mixed states of the ARs

Here, we proposed and developed the application of two new parameters (S_{l-f} and G_S) that may be complementary to the WG_M method. These two parameters are characterising the level of mixed states of sunspot group by estimating their conditional probabilities before the onsets of flares. These parameters may also be suitable new prediction indicators besides the traditional (e.g. Zürich, McIntosh, Mount Wilson) classification schemes that are characterised by alpha-numerical parameters based on morphological data of sunspots and their magnetic fields. The newly defined parameters seem to be viable, as demonstrated by testing them with the currently available most detailed sunspot database, the SDD sunspot catalogue.

Here, we calculated the conditional flare probabilities (CFP) of G_S and S_{l-f} for a period of three days prior to events sampled in every three hours, to determine the probability of flare activity using the two approaches (i.e. the highest-intensity flare and the one of the first flare within the highest-intensity flare-class produced by the ARs). We have drawn the following conclusions from applying the two approaches:

- If $6.5 \leq \log(G_S) \leq 7.5$ then the chances for M-class flaring could be the expected highest intensity with about $\sim$45% for the coming 2 days. However, if the $\log(G_S)$ is larger than 7.5 then the CFP of X-class flare(s) to develop is above at least 70% within 48 hours.
- If $S_{l-f} \leq 1$, there is above at least 70% CFP of the flare being X-class in the following 2 days. If $1 \leq S_{l-f} \leq 3$ then M-class flare(s) could be the highest-intensity increase in the subsequent 48 hours.

The two parameters, introduced here in this Thesis, can also be used in parallel for CME forecast but, unfortunately, the quick fluctuations of G_S itself do not seem to allow to choose this proxy as a single parametric value for forecast in a practical and simple way. Therefore, we suggest to determine its daily average, i.e. the sum of horizontal magnetic gradient, labelled G_{DS}. Moreover, S_{l-f} and G_{DS} should be actually tracked simultaneously *together* in order to estimate the linear speed of a CME. Flares with accompanying fast CMEs (i.e. v_{lin} $\geq$1000 km/s) are only found within 24 hours when $\log(S_{l-f})\leq 0.4$ and $\log(G_{DS})\geq 6.5$. It is also worth mentioning that in only $\sim$30% of all evens is the flare associated with fast CME in the range of $\log(S_{l-f})\leq 0.4$ and $\log(G_{DS})\geq 6.5$, therefore, we need to search for additional precursor(s) of the slow/fast CMEs. So, if $\log(S_{l-f})\geq 0.4$, or $\log(G_{DS})\leq 6.5$, there is no accompanied fast CME in the following 24 hrs.

A reliable forecast procedure is unlikely to be based on a single physical quantity. An accurate variation of probability should include simultaneous parallel methods (and parameters) to which the above suggested proxies may be helpful, among (or complementary to) other methods. In the future, we would like to automate the WG_M method, therefore, here, we seek to find more reliable forecast parameters which could narrow down the identification of larger intensity flaring ARs with an associated fast CME.

Publications in the scope of the Thesis

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2. **Korsós, M. B.,** Ludmány, A., Erdélyi, R. Baranyi, T.: *On Flare Predictability Based on Sunspot Group Evolution*, 2015, *Astrophys. J.*, 802, L21

3. **Korsós, M. B.,** Gyenge, N., Baranyi, T., Ludmány, A.: *Dynamic Precursors of Flares in Active Region NOAA 10486*, 2015, J. Astron. Astropys., 36, pp. 111-121

4. **Korsós, M. B.,** Baranyi, T., Ludmány, A.: *Pre-flare Dynamics of Sunspot Groups*, 2014, *Astrophys. J.*, 789, 107, 7 pp.

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- **Korsós, M. B.,** S. Yang , Erdélyi, R: *Pre-flare dynamic investigation by weighted horizontal magnetic gradient method: From small to major flare class*, 2019, Journal of Space Weather and Space Climate, A6, 12 pp

- **Korsós, M. B.,** Chatterjee, P., Erdélyi, R:. *Applying the Weighted Horizontal Magnetic Gradient Method to a Simulated Flaring Active Region*, 2018, The Astrophysical Journal, 857, 103, 12 pp.

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